

# Physics at ELSA

Hartmut Schmieden<sup>1</sup> and the Crystal-Barrel/TAPS collaboration

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**Abstract.** Recent experimental results of the Crystal-Barrel/TAPS collaboration at ELSA are presented. The experiments used a tagged photon beam incident on proton and neutron targets. Multiple photon final states were detected in the hermetically closed Crystal Barrel/TAPS detector setup, enabling the reconstruction of various neutral meson production channels. In addition to cross sections also photon beam asymmetries and, in the  $K_s^0 \Sigma^+$  channel, recoil polarisations were determined.

**PACS.** 13.60.-r Photon and charged-lepton interactions with hadrons – 13.60.Le Meson production – 13.88.+e Polarization in interactions and scattering – 14.20.Gk Baryon resonances with  $S=0$

## 1 Introduction

The rich excitation spectrum of the nucleon reflects its complicated inner dynamics. Hence baryon spectroscopy is expected to provide benchmark data for any model of the nucleon, e.g. quark models in their variety [1,2] or, increasingly in the near future, Lattice QCD as an approximation of full Quantum Chromodynamics [3]. The major problem of nucleon spectroscopy is the width and density of states involved which, in many cases, prohibit their clean identification, i.e. an unambiguous assignment of quantum numbers within a partial wave analysis.

The current experimental base is mostly restricted to pion and kaon induced reactions. However, a significant number of excited states is suspected to have a strongly disfavoured  $\pi N$  coupling [4]. Hence, such states might have escaped detection in conventional analyses. This is one possible scenario why much less baryonic excitations are observed than expected by quark models and provided the motivation to investigate photoinduced reactions beyond single-pion production [5,6,7]. In particular, we studied  $\eta$  photoproduction off proton and deuteron targets, two-meson final states, associated strangeness photoproduction in the  $K_s^0 \Sigma^+$  channel, and  $\omega$  photoproduction.

Unambiguous solutions of partial wave analyses are generally only possible on the basis of “complete” experiments with regard to the separation of reaction amplitudes. Such measurements appear at the horizon in  $\eta$  and  $K$  photoproduction. In these cases the required number of, if carefully chosen, 8 independent observables [8] seems accessible. In two-meson and vectormeson photoproduction the measurement of the required 16 or 23 quantities is presently out of range. Nevertheless, polarisation observables provide essential constraints which, if not to isolate specific resonances, still may allow to clarify the reaction

mechanism regarding whether s-channel resonances contribute at all.

Such experiments depend on linearly and circularly polarised photon beams. The measurement of double polarisation observables, inescapable for the “complete” experiment, require polarised nucleon targets in addition. Eventually, the recoil nucleon polarisation needs to be determined as well.

In the following section some of the observables of meson photoproduction are discussed. Section 3 then describes the experimental setup before in section 4 some recent, partially preliminary, results are discussed. The final section summarises and gives an outlook to upcoming experiments.

## 2 Cross section and polarisation observables

With polarised beam and target, in the simplest case of photoproduction of single pseudoscalar mesons the cross section can be written in the form [9]

$$\begin{aligned} \frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} [ & 1 - P_{\text{lin}} \Sigma \cos 2\Phi \\ & + P_z (-P_{\text{lin}} H \sin 2\Phi + P_{\text{circ}} F) \\ & - P_y (-T + P_{\text{lin}} P \cos 2\Phi) \\ & - P_z (-P_{\text{lin}} G \sin 2\Phi + P_{\text{circ}} E)], \end{aligned} \quad (1)$$

where  $\sigma_0$  denotes the polarisation independent cross section,  $P_{\text{lin,circ}}$  the degree of linear or circular polarisation of the incident photon beam, and  $\Phi$  the azimuthal orientation of the reaction plane with respect to the plane of linear polarisation. The photon direction defines the  $z$  axis of a right handed coordinate frame spanned with the outgoing meson momentum  $\mathbf{k}_m$ :  $\mathbf{z} = \mathbf{k}_\gamma/|\mathbf{k}_\gamma|$ ,  $\mathbf{y} = \mathbf{k}_m/|\mathbf{k}_m|$ , and  $\mathbf{x} = \mathbf{z} \times \mathbf{y}$ .  $P_{x,y,z}$  are the cartesian components of

the target polarisation vector in this frame. Once beam and/or target are polarised, the polarisation observables  $\Sigma$ ,  $H$ ,  $F$ ,  $T$ ,  $P$ ,  $G$  and  $E$  are accessible. In particular, the measurements require the following combinations of beam and target polarisation:

| observable | beam     | target       |
|------------|----------|--------------|
| $\Sigma$   | linear   | no           |
| $T$        | no       | transverse   |
| $H$        | linear   | transverse   |
| $F$        | circular | transverse   |
| $P$        | linear   | transverse   |
| $G$        | linear   | longitudinal |
| $E$        | circular | longitudinal |

The polarisation observables represent ratios of structure functions and as such are related to the more general case of meson electroproduction. Although more involved than photoproduction, through variation of the momentum transfer electroproduction is able to characterise the spatial structure of the processes involved [10] in addition to the time structure which is obtained through the spectroscopic information with real photons. If instead of, or, in addition to target polarisation the measurement of nucleon recoil polarisation is provided, further double and triple polarisation observables can be defined which, with their mutual interrelations, are discussed in detail in [9].

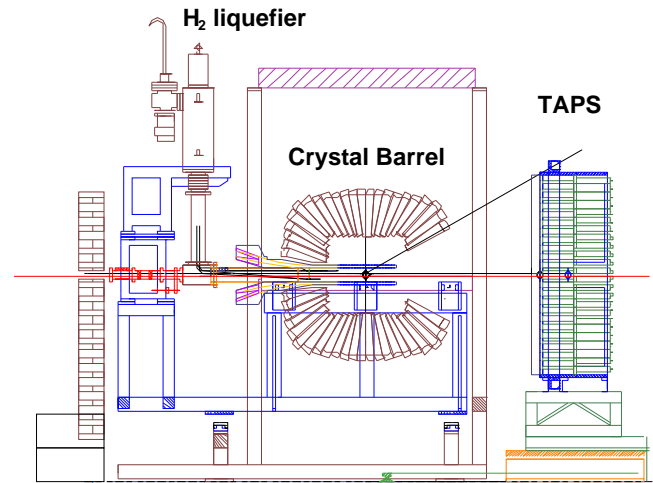
In the sense of the “complete” experiment mentioned in the introduction, it is necessary to determine angular distributions of at least 8 quantities. Those must encompass the differential cross section and the single polarisation observables  $\Sigma$  and  $T$ , as well as the recoil polarisation. Furthermore, 4 double polarisation, e.g. beam-target, observables need to be chosen such that the occurrence of discrete ambiguities can be avoided in the analysis of the bilinear forms of the reaction amplitudes [8].

The situation becomes more complicated in the photoproduction of double pseudoscalars [11] and vector mesons. Despite the infeasibility of “complete” experiments with current techniques in such cases, essential information towards the involved reaction mechanisms, in particular the role of s-channels resonances, can be expected from the investigation of single and double polarisation observables.

The understanding of the reaction mechanisms is a prerequisite for partial wave analyses (PWA) or dynamical models to disentangle the broad and overlapping states. Different final states and concurring (coupled) channels need to be investigated as well as proton and neutron targets. In addition to polarisation, also full coverage of the angular and energy range is essential. Thus, the combination of the Crystal Barrel [12] and TAPS [13] detectors to an almost  $4\pi$  array at the Bonn electron stretcher accelerator ELSA [14] provides an ideal tool for the sketched investigations.

### 3 Experimental setup

The experiments were performed at the tagged photon beam of ELSA. Electron beams up to  $E_0 = 3.5$  GeV were



**Fig. 1.** Setup of the detector system as described in the text. The photon beam enters from left.

used to produce unpolarised or linearly polarised [15,16] bremsstrahlung. Electrons which radiated a photon were momentum analysed in a tagging spectrometer, enabling the event-wise assignment of the photon energy in the range  $E_\gamma = 0.18 \dots 0.92 E_0$ . Photon fluxes of about  $2 \times 10^7 \text{ s}^{-1}$  were usually used.

The detector setup is depicted in Figure 1. The photon beam hit a 5.3 cm long liquid hydrogen or deuterium target. A three layer scintillating fibre detector [17], which surrounded the target within the polar angular range from 15 – 165 degrees, was used to determine a point-coordinate for charged particles.

Both, charged particles and photons were detected in the Crystal Barrel detector [12]. Its 1290 individual CsI(Tl) crystals were cylindrically arranged around the target in 23 rings, covering a polar angular range of 30 – 168 degrees. For photons an energy resolution of  $\sigma_{E_\gamma}/E_\gamma = 2.5\%/\sqrt{E_\gamma/\text{GeV}}$  and an angular resolution of  $\sigma_{\theta,\phi} \simeq 1.1$  degree was obtained.

The 5.8 – 30 degree forward cone was covered by the TAPS detector [13], set up in one hexagonally shaped wall of 528 BaF<sub>2</sub> modules at a distance of 118.7 cm from the target. For photons between 45 and 790 MeV an energy resolution of  $\sigma_{E_\gamma}/E_\gamma = (0.59/\sqrt{E_\gamma/\text{GeV}} + 1.9)\%$  was achieved [18]. The position of photon incidence could be resolved within 20 mm. For charged particle recognition each TAPS module had a 5 mm plastic scintillator in front of it.

### 4 Recent Results

The combined Crystal Barrel and TAPS setup is ideally suited for final states of multiple photons. Hence, neutral mesons are very efficiently detected. Those are of particular interest for nucleon spectroscopy since t-channel exchanges, which may hide resonance excitations, are suppressed in many cases. Investigated channels involve  $\pi^0 \rightarrow$

$\gamma\gamma$ ,  $\eta \rightarrow \gamma\gamma$  or  $3\pi^0$ ,  $K_s^0 \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$ , and  $\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$ , as well as combinations thereof. Typical invariant mass resolutions achieved were  $\sigma_{\pi^0} = 10$  MeV and  $\sigma_\eta = 22$  MeV in the two-photon decays of  $\pi^0$  and  $\eta$ , and  $\sigma_\eta = 25$  MeV in  $\eta \rightarrow 3\pi^0$ .

#### 4.1 $\eta$ photoproduction off the proton

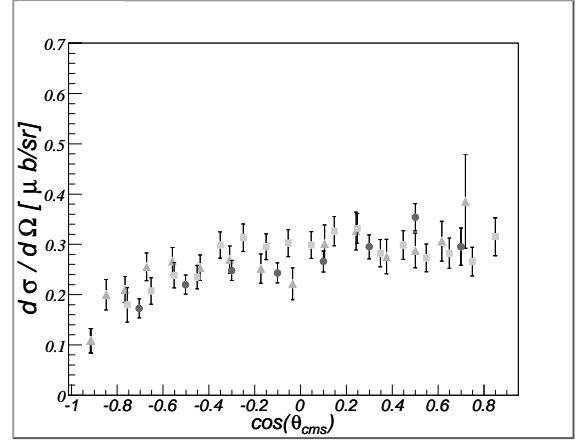
Similar to pion photoproduction by the  $\Delta(1232)$  resonance so is  $\eta$  photoproduction in the threshold region dominated by a single nucleon resonance, the  $S_{11}(1535)$ . Vice versa,  $\eta$  photoproduction gives very selective access to this state, the internal structure of which is still under debate. Furthermore,  $\eta$  photoproduction is a predestined channel to look for possible resonances with small  $\pi$ -N coupling which might have escaped experimental detection to date. Due to its isoscalarity, the  $\eta$  only connects  $N^*$  as opposed to  $\Delta^*$  resonances with the nucleon ground state, which simplifies the observed spectrum considerably.

The role of resonances beyond the  $S_{11}$  is, due to its dominance, much less clear. The strategy to investigate this at ELSA was threefold: First, differential cross sections have been determined over the full angular range across the full nucleon resonance region. Second, as a first step towards the “complete” experiment the photon beam asymmetry has been measured at the high-energy tail of the  $S_{11}$ . And third, neutron targets have been included in the investigations as will be discussed later.

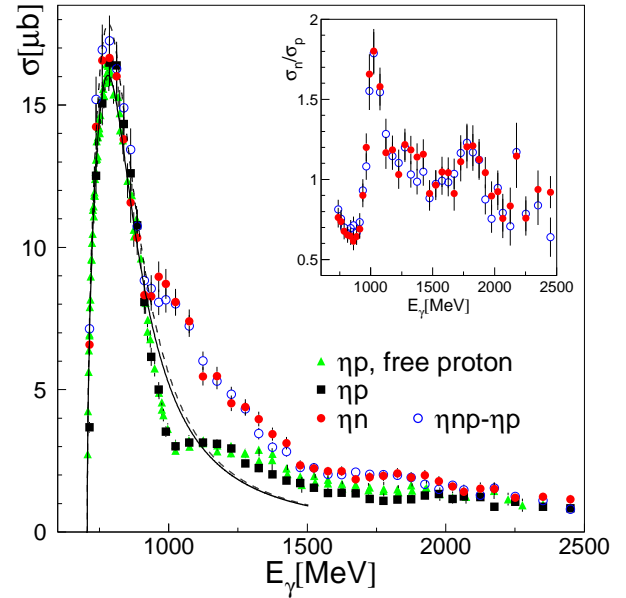
A recent cross section measurement of the Crystal Barrel Collaboration at ELSA provided some indication for a yet unobserved  $N^*(2070)D_{15}$  state [5, 19]. The data agree well with the CLAS data which are available at somewhat lower energy [20], but both data sets are normalised only relative to the SAID  $\pi^0$  cross section. This deficiency could now be remedied by a detailed analysis of the photon flux based on the timing and rate information of the tagging system [21]. The preliminary result for one energy bin is shown in Figure 2. In addition to the absolute normalisation, the full data set, which presently is in the final analysis stage, has also improved angular coverage in forward direction as well as improved statistics compared to the published data of ref. [19].

Using a linearly polarised photon beam, the photon beam asymmetry  $\Sigma$  was measured [15, 16] based on the azimuthal modulation of the cross section (cf. Eq. 1). The results agree well with the measurements at GRAAL [22, 23]. In the light of the introductory discussion the measurement of  $\Sigma$  is absolutely indispensable to disentangle the resonances possibly contributing to the reaction. The analysis of the new Crystal Barrel data within the MAID isobar model [24] and the Bonn-Gatchina PWA [25] showed, however, that no unambiguous conclusion can yet be drawn. Both MAID and the Bonn-Gatchina partial wave analysis provide a satisfactory overall description of our data. In detail, however, there are marked differences with regard to the role of individual resonance contributions, cf. the figures and detailed discussion in [15, 16].

To resolve this problem, further double polarisation experiments are indispensable.



**Fig. 2.** Preliminary differential cross section with absolute normalisation of Crystal Barrel/TAPS [21] (triangles) in the bin  $E_\gamma = (1075 \pm 25)$  MeV in comparison to earlier measurements from Crystal Barrel [19] (squares) and CLAS [20] (circles) which are normalised relative to the SAID  $\pi^0$  photoproduction database.



**Fig. 3.** Preliminary result for the total cross sections of  $\eta$  photoproduction off the deuteron. Squares denote the quasifree  $\eta$  production off the bound proton, filled circles off the neutron. The Fermi smearing has been unfolded. The open circles represent the difference between total quasifree production off the deuteron and the elementary production of the free proton. The latter is individually shown by the triangles. The insert depicts the ratio of neutron over proton cross section.

#### 4.2 $\eta$ photoproduction off the neutron

Off the neutron,  $\eta$  photoproduction had attracted a lot of activity recently. The reason is a rather narrow structure which seemed to exhibit itself in the cross section [26]. Also in the preliminary Crystal Barrel/TAPS data which are presented in Figure 3 there is a clear structure visible

in the neutron cross section at around  $E_\gamma \simeq 1100$  MeV [27]. Such a bump is present neither in the free nor the quasifree proton cross section. This had triggered speculations about the influence of a narrow (antidecuplet) state [29]. However, conventional explanations are also possible, albeit the nature of the structure still remains under debate.

Interferences within the  $S_{11}$  partial waves, e.g. between  $S_{11}(1535)$  and  $S_{11}(1650)$ , seem to play a crucial role, both within the Bonn-Gatchina PWA [30] and the Giessen coupled channels model [31]. Interferences between different partial waves,  $S_{11}(1535)$  and  $D_{13}(1520)$  are under discussion, do exhibit in the angular distributions, but those can not affect the *total* cross section. The direct contribution of the  $D_{13}(1520)$  is much too small to become responsible for the bump. This may be different for the  $D_{15}(1675)$  state. Within the MAID model it has a particularly strong coupling to the neutron, at the same time however also an unusual nucleon- $\eta$  decay branch of 17 %, in disagreement with the PDG value of 0 – 1 %. To clarify this still unsatisfactory situation, measurements of  $\Sigma$ ,  $E$  and  $G$  are planned [28].

### 4.3 $K_s^0 \Sigma^+$ photoproduction

There are substantial decay branches of baryon resonances expected into  $K$ -hyperon channels [32,33]. Hence, associated strangeness photoproduction is also a channel where so far unobserved states of the quark models may be found. The reaction mechanism should become disentangled once the complete experiment is approached with regard to the reaction amplitudes. To achieve this, the  $K \Lambda/\Sigma$  channels are very well suited due to the self analysing weak decay of the hyperons. This facilitates the indispensable measurement of the recoil polarisation.

The  $K^0 \Sigma^+$  channel has been investigated with Crystal Barrel/TAPS from threshold to  $W = 2.3$  GeV. In a first step cross sections and recoil polarisation were determined [34] and compared to calculations within the Bonn-Gatchina PWA [25,36] and a coupled-channels K-matrix formalism of Usov and Scholten [37]. The total cross section is well reproduced by both calculations. However, an additional new state at about 1840 MeV is required which in the PWA analysis has  $P_{11}$  quantum numbers, in contrast to  $P_{13}$  in the Usov-Scholten model. Such an ambiguity is no surprise given the “incompleteness” of the present experiments. It will be remedied with the availability of polarisation observables.

The first measurement of the recoil hyperon polarisation with Crystal Barrel/TAPS [34] has been statistically improved in the meanwhile and, in addition, the photon beam asymmetry has been measured [35]. Preliminary results are shown in Figure 4.

### 4.4 Two pseudoscalar meson channels

Double meson final states provide a tool to get access to high-lying excitations which decay sequentially. Data of

$\pi^0 \pi^0$  and  $\pi^0 \eta$  final states were taken over the entire resonance region [42,43,44].

From the  $2\pi^0$  channel partial decay widths of  $N^*$  and  $\Delta^*$  decaying into  $\Delta(1232)\pi$ ,  $N(\pi\pi)_s$ ,  $P_{11}(1440)\pi$  and  $D_{13}(1520)\pi$  were determined [39]. The PWA is compatible with known resonance properties. The largest difference to the PDG value is found for the total decay width of the  $P_{13}(1720)$ . From the analysis of the Roper  $P_{11}$  partial wave a strong coupling of the  $N(1440)$  to  $N\sigma$  is suggested [40].

Due to the isoscalar  $\eta$ , the  $\pi^0 \eta$  final state provides selectivity to  $\Delta^*$  intermediate states. Based on the unpolarised data, the Bonn-Gatchina PWA finds a  $D_{33}$  partial wave with contributions from  $\Delta(1700)$  and  $\Delta(1940)$  [41]. Possibly, also a further  $\Delta(2350)$  adds weakly. The  $\Delta(1940)$  is a highly interesting negative parity state. In quark models it would be interpreted as a radial excitation of the  $\Delta(1700)$ . However, the mass is unexpectedly low by about 200 MeV.

New measurements with linearly polarised photon beam show clear beam asymmetries in both the  $\pi^0 \pi^0$  and  $\pi^0 \eta$  channels [42,43,44]. The cross section for the production of two pseudoscalar mesons can be written in the form

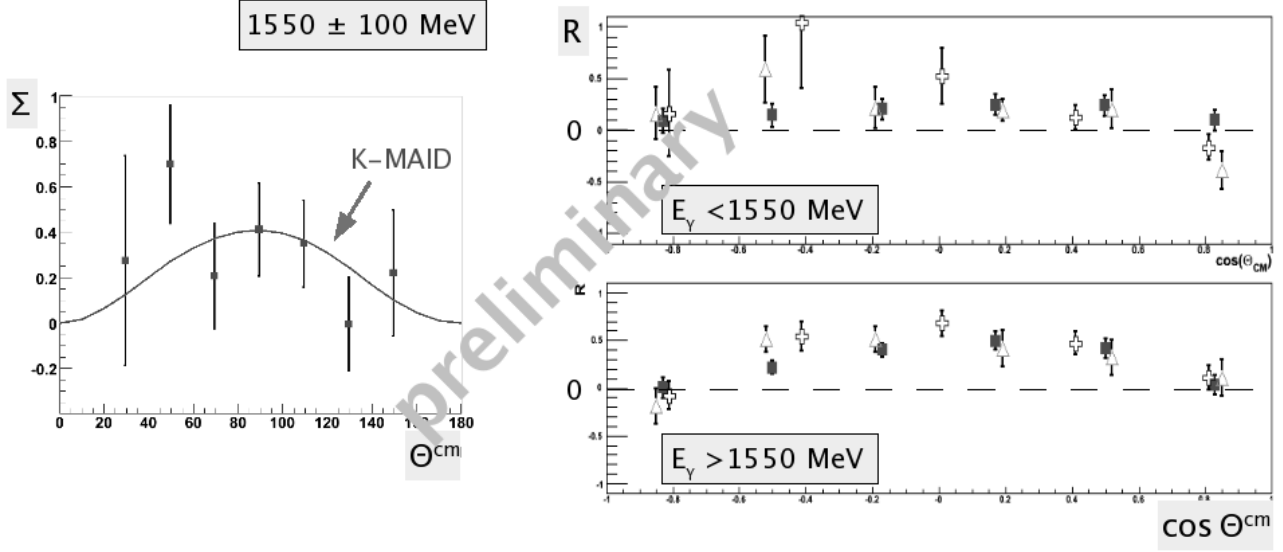
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \{1 - P_{\text{lin}} (\Sigma \cos 2\Phi + I^S \sin 2\Phi)\}. \quad (2)$$

Due to the 3-body final state, compared to Eq. 1 an additional asymmetry  $I^S$  occurs which exhibits through a  $\sin 2\Phi$  azimuthal modulation. This is however found to be compatible with zero in both final states. The  $2\pi^0$  asymmetries agree well with GRAAL data published for the lower energies [45].

### 4.5 $\omega$ photoproduction

Previous near-threshold measurements of  $\omega$  photoproduction [47] had been interpreted in terms of s-channel resonances [48]. However, to disentangle resonance contributions from the important t-channel exchange of  $\pi^0$  and/or pomeron, polarisation observables are essential [49]. This motivated us to investigate the beam asymmetries in  $\omega$  photoproduction using the  $\omega \rightarrow \pi^0 \gamma$  decay. In addition to the ordinary  $\Sigma$  of Eq. 1, in the  $\pi^0 \gamma$  decay also the decay asymmetry  $\Sigma_\pi$  can be accessed, which is related to the azimuthal modulation of the direction of the *decay pion* with respect to the photon polarisation plane. Various models predict large negative  $\Sigma$ 's if s-channel resonances contribute [50]. In this case the Bonn-Gatchina PWA expects  $\Sigma_\pi \simeq 0$ . In contrast, pure t-channel mechanisms would generate  $\Sigma_\pi = \pm 0.5$ .

Experimentally the  $\omega$  is clearly identified in its neutral decay yielding  $3\gamma$ . However, even with the close to  $4\pi$  coverage, a number of background channels contribute significantly, mostly due to missing one photon of competing reactions with 4 final state photons, or having a split-off from a 2 photon final state. The shaded histogram of Figure 5 shows the  $\pi^0 \gamma$  invariant mass distribution. The indicated background channels yield a reasonable Monte-Carlo description of the spectrum. In the region of the  $\omega$



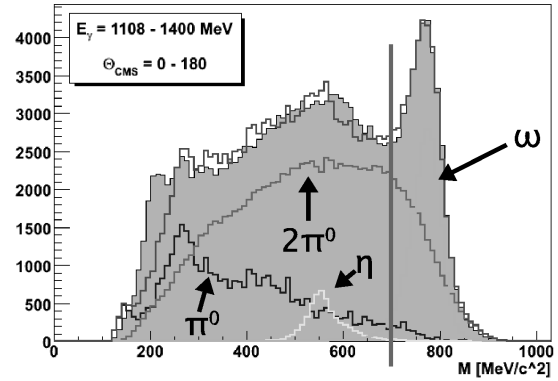
**Fig. 4.** Preliminary polarisation results in  $K_s^0 \Sigma^+$  photoproduction off the proton [35]. *Left:* Photon beam asymmetry as a function of the  $K$  cm-angle in the energy interval 1450–1650 MeV. The errors correspond to the statistics of about a quarter of the full data set. The curve represents the K-MAID calculation. *Right:* Recoil hyperon polarisation in two energy intervals. The preliminary data [35] (squares) are compared to the previous measurements of Crystal Barrel/TAPS [34] (triangles) and SAPHIR [38] (crosses).

peak the far dominating part of the background is from  $2\pi^0$ . Therefore, to subtract the background, so far bin-wise fits have been performed of signal plus  $2\pi^0$  debris to the experimental distributions. From the corresponding event numbers within  $\pm 2.5\sigma$  wide cuts around the peak the azimuthal distributions and the asymmetries were determined.

As examples, preliminary results for  $\Sigma$  and  $\Sigma_\pi$  are shown in Fig. 6 in the bin of  $E_\gamma = (1250 \pm 100)$  MeV. Good agreement is found to a recent measurement of  $\Sigma$  from GRAAL [51]. Compared to GRAAL the ELSA dataset extends the energy range to  $E_\gamma = 1700$  MeV.  $\Sigma_\pi$  (Fig. 6 bottom) is only accessible in the  $\pi^0 \gamma$  decay channel measured at ELSA. Both the large negative  $\Sigma$  and the small  $\Sigma_\pi$  seem to further support that s-channel resonances provide a substantial contribution to  $\omega$  photoproduction. However, a closer characterisation of individual contributions appears premature without the measurement of further double polarisation observables, which has just started at ELSA [49].

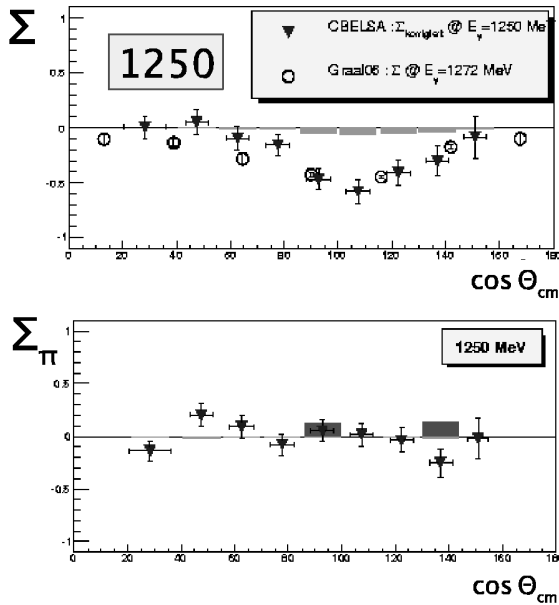
## 5 Summary and outlook

Using the tagged photon beam of ELSA and the combined Crystal Barrel/TAPS setup several neutral meson photoproduction channels have been investigated. From the differential and total cross sections indeed indications have been found for previously unseen states. Before however unambiguous conclusions from PWA or dynamical models are possible, single and double polarisation observables need to be measured as well. As a first step, photon beam



**Fig. 5.**  $\pi^0 \gamma$  invariant mass distribution (shaded histogram). As a result of Monte Carlo studies, the lines show the  $\omega$  signal peak and main background contributions as indicated. The vertical line represents the minimum invariant mass required in the extraction of the asymmetries [46].

asymmetries and, in the  $K_s^0 \Sigma^+$  channel, recoil polarisations have been determined to further constrain the analyses. Double polarisation experiments have been prepared at ELSA and are currently underway, using the longitudinally polarised electron beam in combination with the longitudinally polarised frozen spin target. Similar plans are pursued at several other laboratories. The double polarisation experiments are expected to nail down the question of the existence of at least some of the newly found states.



**Fig. 6.** Preliminary results (filled triangles) of the beam asymmetry (upper diagram),  $\Sigma$ , and the decay asymmetry,  $\Sigma_\pi$  (lower diagram) for the energy bin  $E_\gamma = 1250 \pm 100$  MeV. GRAAL data (open circles) of  $\Sigma$  are shown for comparison. Purely statistical errors are attached to the data points, the bars represent estimates of the systematic uncertainties.

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